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13. ABSTRACT (Maximum 200 words) Resin flow in resin transfer molding may be strongly influenced by small heterogeneities in the fiber preform, such as narrow channels formed by bending and fitting into a mold. An evaluation of preform permeability in these regions of nonuniform packing was studied. The study incorporated an empirical and analytic approach to iteratively determine the permeability in these regions. Flow front data were recorded for high fiber volume fraction woven fiber preforms. Two studies were conducted: one study addressed permeability associated with edge gaps, a second study addressed gaps caused by bending a fiber mat over a 90 degree mold edge. In the edge gap study, edge gap width, injection pressure and fiber volume fractions were varied. The flow front data were compared with numerical simulations to estimate enhanced permeability at the edges. The results indicate that, for high fiber volume fraction preforms, flow in the channel dominates for relatively small (approx. 2 mm) gaps. In the corner permeability study, the inside corner radius was varied, and the fiber volume fraction was held constant at 45%. The results indicate that racetracking can be significant for some configurations.				
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Determination of Corner and Edge Permeability
in Resin Transfer Molding

Final Progress Report

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1 Foreword

Resin flow in resin transfer molding may be strongly influenced by small heterogeneities in the fiber preform, such as narrow channels formed by bending and fitting into a mold. An evaluation of preform permeability in these regions of nonuniform packing was studied. The study incorporated an empirical and analytic approach to iteratively determine the permeability in these regions. Flow front data were recorded for high fiber volume fraction woven fiber preforms. Two studies were conducted: one study addressed permeability associated with edge gaps, a second study addressed gaps caused by bending a fiber mat over a 90° mold edge.

In the edge gap study, edge gap width, injection pressure and fiber volume fractions were varied. The flow front data were compared with numerical simulations to estimate enhanced permeability at the edges. The results indicate that, for high fiber volume fraction preforms, flow in the channel dominates for relatively small (≈ 2 mm) gaps.

In the corner permeability study, the inside corner radius was varied, and the fiber volume fraction was held constant at 45%. The results indicate that racetracking can be significant for some configurations. Additional studies are recommended to determine the gap associated with combinations of corner radius and preform fiber volume fraction. With this additional data, the edge gap results could be readily compared with the corner permeability study.

Contents

1	Foreword	1
2	Problem Statement	3
2.1	Edge Permeability Study	3
2.2	Corner Permeability Study	4
3	Results Summary	4
3.1	Experimental Results	4
3.2	Computational Results	6
4	Publications and technical reports	6
4.1	Theses	6
4.2	Manuscripts	6
5	Participating scientific personnel/students	6
6	Report of Inventions	7
	References	7

List of Figures

1	Schematic showing racetracking along the edge of a flat mold for resin transfer molding.	4
2	Schematic showing racetracking along the corner in a corner mold for resin transfer molding.	5

2 Problem Statement

Resin Transfer Molding (RTM) is a flexible manufacturing process capable of producing high performance composite parts. RTM is attractive both in the aerospace industry, where high performance parts are the goal, and in the ground vehicle industry, where low cost and high volume are more of a concern. In resin transfer molding, resin is injected under pressure into a heated mold cavity which contains a fiber preform. The process allows a variety of preform materials, resins and mold geometries. This flexibility enables the design of complex parts ranging from small to very large with structural performance tailored to a particular application [1].

RTM is a versatile process, but determining the mold design and process conditions is not straightforward. The resin must fill the mold and impregnate the fiber without leaving any air pockets or dry spots (voids). These voids create stress concentrations that reduce the strength of the part. Void size and location depend on resin and fiber types, flow geometry, and process conditions. Macroscopic voids can be reduced by knowing in advance how the fluid will flow throughout the mold and placing vent holes accordingly. Microscopic voids within the fiber tows can be reduced [2] through knowledge of fiber tow orientations and necessary pressure gradients. Each new design means a new set of conditions affecting the fiber impregnation and filling of the mold. Lack of past experience and the variety of designs result in processing conditions being determined empirically. An alternative to the time delay and high cost of the empirical experiments is sought.

Numerical models can simulate resin injection for a wide range and combination of polymers, fibers, and even mold shapes. These simulation provide the designer the necessary knowledge to choose gate and vent locations in order to eliminate dry spots. One of the major shortcomings of these models is the difficulty in providing model inputs, particularly the fiber preform characteristics. The fiber preform may consist of a single woven or random fiber mat or several mats stitched together. The fiber preform provides resistance to the resin flow, this resistance is quantified by a preform permeability. Higher permeability corresponds to lower flow resistance. When the preform is placed in the mold, often this packing is not uniform, especially for complex mold geometries and at corners and edges of the mold. In these regions of non uniform packing, fiber preform permeability will vary from its nominal value (referred to as the bulk permeability). The goal of this research was to quantify these regions of enhanced (or diminished) permeability. The particular emphasis is on edges and corners in molds, which can cause gaps between the preform and mold.

2.1 Edge Permeability Study

A mold of constant thickness b , length L and width w is packed with a woven fiber preform. There is a uniform gap of width h between the preform edge and mold. Resin is injected into the mold under constant pressure at a single gate located at the mold end (Figure 1). The fluid flow front position as a function of time is recorded during mold filling. The objective of this research is to determine effective gap permeabilities associated with race tracking along the mold edge.

In our approach, experimentally determined flow front positions are compared with RTM model simulations. The gap permeability required to simulate the flow front is adjusted until there is good agreement with the flow front data. Gap permeabilities are evaluated for high v_f woven fabric preforms over a variety of injection pressure and gap widths.

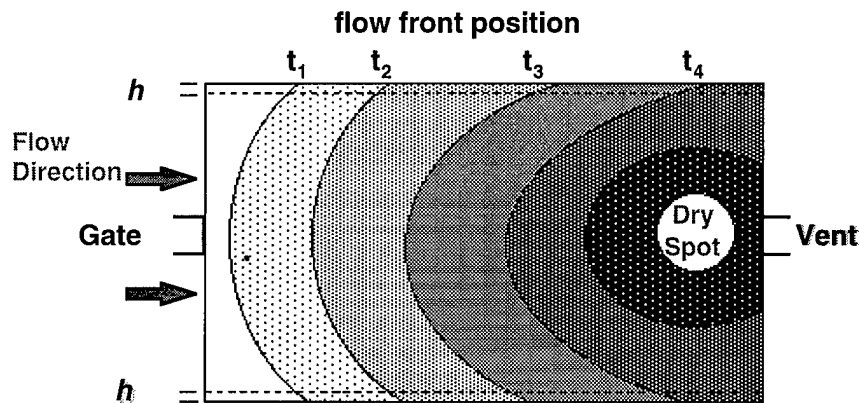


Figure 1: Schematic showing racetracking along the edge of a flat mold for resin transfer molding.

2.2 Corner Permeability Study

In the corner permeability study, a corner mold of constant thickness with variable corner radii (both inside and outside) was constructed (Figure 2). Resin was injected at two inlet ports. Each port was located at the narrow edge of the mold, one port for each side, such that the resin flowed along the mold length and parallel to the corner. In this way, the corner behaved similar to the edge in the flat plate experiments. Experiments were conducted for various radii with a woven fiber mat. The fiber volume fraction in the mold side area was 45%. In the corner, a gap formed as the mat was draped over the corner. Flow front simulations were run to estimate the permeability at the corner as a function of the mold corner radii and bulk permeability.

3 Results Summary

3.1 Experimental Results

Both the edge and corner permeability studies indicated that, for high fiber volume fraction preform materials ($> 0.45\%$), small gaps (on the order of 2 mm) cause significant race-tracking. Gap permeability was almost 900 times greater than bulk permeability for this case. Because the gap permeability can be significantly affected by small changes in gap size, preform cutting and placing procedures are critical.

A nondimensional parameter was introduced, $h/\sqrt{K_{bulk}}$, which allows comparison of data over a range of preform fiber volume fractions. In this parameter h is the edge or channel gap and K_{bulk} is the preform bulk permeability and is a function of the fiber volume fraction. In fact, the data from the experiments performed under this contract at the University of Minnesota (reported in [3]) compares favorably with a similar graph from Bickerton and Advani [4]. Both sets of data show similar ranges of scaled edge permeability values, even though fiber volume fraction and preform geometries are dramatically different.

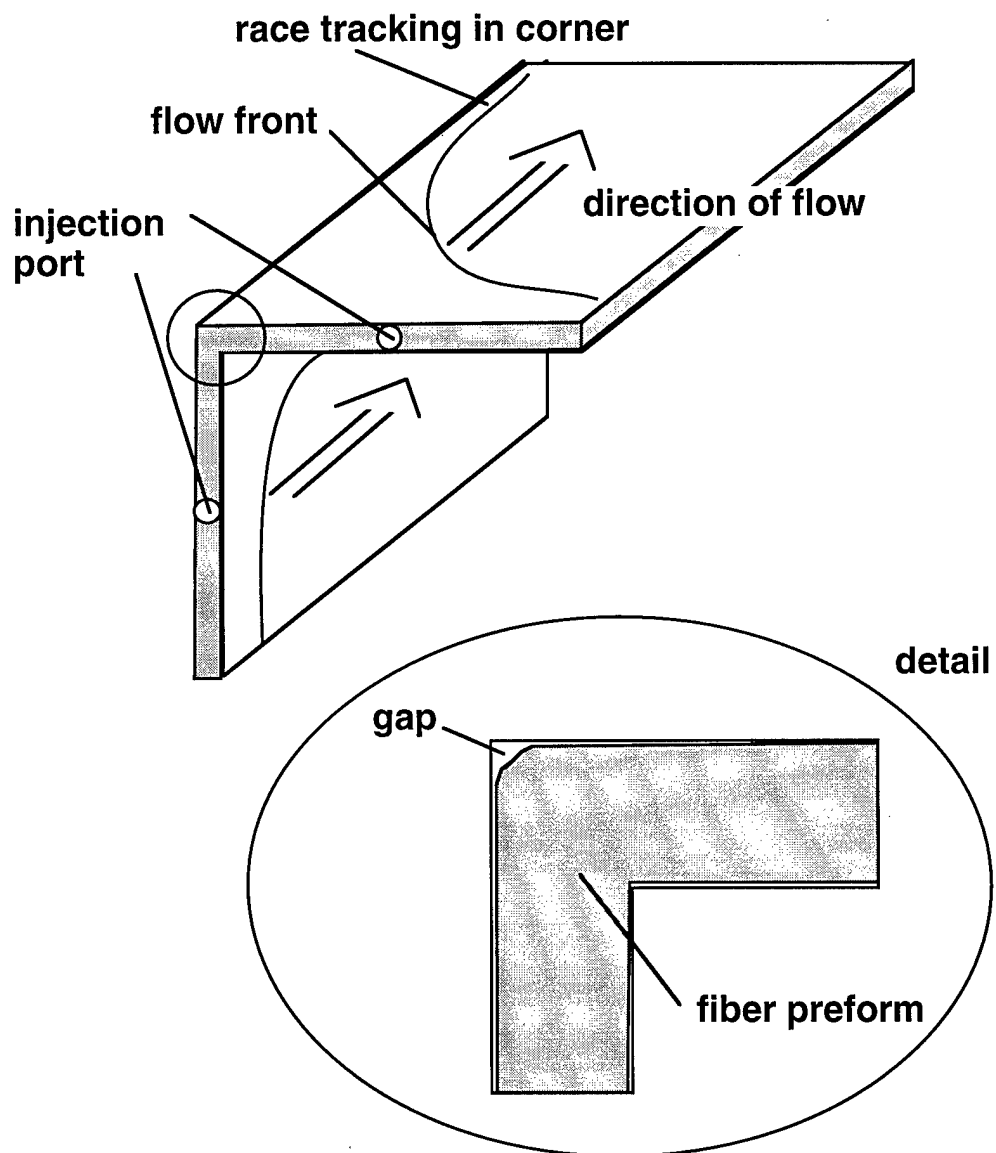


Figure 2: Schematic showing racetracking along the corner in a corner mold for resin transfer molding.

We also developed a unique repeatable method for preform preparation ([3]). This method involves casting the preform mat in Napthalene prior to cutting to ensure close tolerances for the channel width. Once the mat is in place in the visualization mold, the cast material is evaporated off, leaving the mat precisely located within the mold.

3.2 Computational Results

A finite element based computer model was developed to simulate resin transfer molding. A unique feature of this model is that any number of unknown modeling parameters may be determined by computer optimization. For example, in determining the edge permeability K_{edge} the computer prediction of flow front position as a function of time was compared to experimental data. The value for K_{edge} was iteratively determined by minimizing the differences between the two flow fronts following an optimization algorithm.

4 Publications and technical reports

4.1 Theses

Duh, R. J.-Y., *Polymer Kinetics Parameter Estimation for Structural Reaction Injection Molding/Resin Transfer Molding*, Ph. D. Thesis, Department of Mechanical Engineering, University of Minnesota, 1996.

Sheard, J., *Determination of Fiber Preform Permeability Along Edges in Resin Transfer Molding*, M.S. Thesis, Department of Mechanical Engineering, University of Minnesota, 1996.

Senft, V. J., *Edge and Corner Visualizations in Resin Transfer Molding*, M.S. Thesis, Department of Mechanical Engineering, University of Minnesota, draft complete, will be defended Fall 1997.

4.2 Manuscripts

Duh, R.J.-Y., R.S. Maier, and J.H. Vogel, "Experimental Estimation of Process Parameters in Resin Transfer Molding," 27th International SAMPE Technical Conference, Vol. 27, pp. 472-483, October 9-12, 1995.

Sheard, J., V. Senft, S.C. Mantell, J.H. Vogel and R.S. Maier, "Determination of Corner and Edge Permeability in Resin Transfer Molding," *Polymer Composites*, Accepted August 1997.

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6 Report of Inventions

none

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- [4] S. Bickerton and S.G. Advani. Characterization of corner and edge permeabilities during mold filling in resin transfer molding. In *Recent Advances in Composite Materials*, Volume 56, pages 143–151. American Society of Mechanical Engineers, Materials Division, 1995.